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Low cost butane propulsion systems for small spacecraft

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Abstract

This paper describes the work performed at the Surrey Space Centre to produce low cost propulsion systems for small spacecraft with relatively low velocity-change (ΔV) requirements. Traditionally, cold gas nitrogen systems have been used for this type of application, however these have high storage volume requirements which can be a problem given the typical volume constraints of small spacecraft. An alternative solution is to use liquefied gases, which store as liquids and hence have reasonable densities, whilst still being suitable for use in a cold gas thruster. Thus, liquefied butane gas has been selected as our propellant of choice: Although it has slightly lower specific impulse than nitrogen, it has a significantly higher storage density, and, conveniently, it stores at a very low pressure, hence no pressure-regulation system is required.

On 28th June 2000 Surrey launched its first nano-satellite: SNAP-1. This spacecraft was equipped with a small cold gas propulsion system utilising 32.6 grams of butane propellant, which, since launch, has been used to raise the spacecraft's semi-major axis by over 3 kilometres. In this paper, we describe SNAP-1's propulsion system, highlighting its low-cost features. Telemetry data are used to illustrate orbital control operations, and to derive an overall mission specific impulse.

Surrey Satellite Technology Ltd (SSTL) are currently under contract to build three Earth-observation spacecraft for a Disaster Monitoring Constellation (DMC). Each spacecraft will weigh approx 100 kg and have a ΔV requirement of 10 m/s. A new butane system is being designed and manufactured to meet the requirements of these spacecraft. The system is based very much on the flight heritage of the SNAP-1 system, but with the addition of greater propellant storage capacity. The lessons learnt from SNAP-1 operations are reviewed and the resulting design improvements for the DMC propulsion system are detailed.

Introduction

To date (June 2001), Surrey has designed, constructed and launched 19 small spacecraft into low Earth orbit (LEO). So far, only two of these have had on-board propulsion systems. However there is a changing trend, and most of our future spacecraft will contain propulsion systems. Propulsion is required for:

- constellation formation and maintenance;
- drag compensation to keep the spacecraft altitude constant;
- attitude control via small thrusters;
- de-orbiting at the end of life;
- formation flying of clusters of spacecraft.

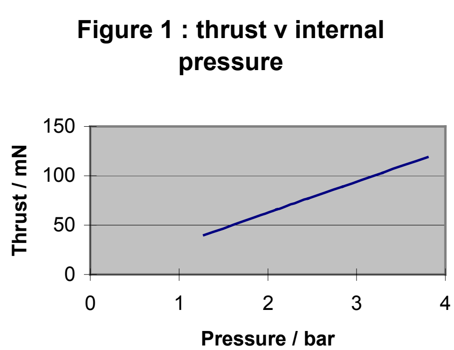
If de-orbiting of the spacecraft at end of life is not a design requirement, then typical LEO missions will have ΔV requirements of less than 20 m/s. Traditionally this will have been met using a cold gas nitrogen propulsion system. From a small satellite point of view, the main disadvantage of nitrogen is the fact that it stores at a relatively low density - even at high pressures, hence the volume of the propellant tank tends to be large. This can be a problem, as small spacecraft are often more volume-constrained than mass-limited. Liquefied gases offer a better alternative, as they store as liquids, and hence tankage volumes can be reduced [1].

Butane is the current propellant of choice for Surrey's small spacecraft. It stores as a liquid with a storage density of 0.53 g/cm^3 (compared to only 0.22 g/cm^3 for nitrogen at 200 bar pressure). It has a theoretical specific impulse of 70 seconds, which is only 10% less than nitrogen. Hence the density I_{sp} (impulse per unit volume of propellant) of butane is 362 Ns per litre compared to 165 Ns per litre for nitrogen. The consequence of this is that, for a given mission impulse requirement, butane will store in a much smaller volume. An additional advantage is that butane has a very low storage pressure. At 20ºC, its vapour pressure is 2.1 bar absolute. This has two significant advantages: Firstly, a traditional thin wall spacecraft tank (typically designed for 20 bar) will be very robust with butane, giving large safety factors. Secondly, the system's thrusters can be designed to use 2 bar as a practical chamber pressure and hence no complex regulation system is needed. This reduces the number of expensive valves required in a system.

A drawback with the use of butane is that it must be expelled in gaseous form. If liquid phase butane is expelled, then the specific impulse obtained from the thruster is reduced dramatically. Hence a heater is required to ensure that only vapour phase butane is vented.

Figure 1 shows the relationship between the system pressure and the thrust (assuming no liquid phase butane is expelled).

The system pressure is the same as the butane vapour pressure and hence is linearly related to the butane temperature. Therefore by controlling the temperature of the system, the thrust levels can be controlled. For example if the spacecraft's ambient temperature is 20°C, then as already noted, the butane vapour pressure will be 2.1 bar, giving nominal thrust of 65 mN.



A further advantage of this type of system is that very small Minimum Impulse Bits (MIBs) of less than 1 mNs can be achieved.

SNAP-1

System description

SNAP-1 was the UK's first nano-satellite project, designed and constructed by Surrey Space Centre and SSTL staff with SSTL funding. The whole spacecraft had a wet-mass of 6.5 kg. Figure 2 shows the interior of the SNAP-1 platform. It is constructed from 3 sets of electronic module boxes, connected together to form a triangular structure. The small size of the spacecraft is apparent from the scale of the hand in the picture.

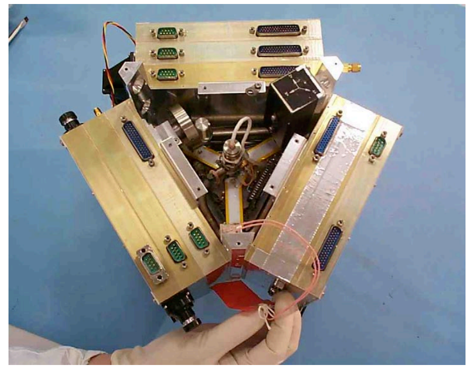


Figure 2: SNAP-1 Internal Structure

The propulsion system fits within the central triangular space, with a single thruster positioned along the central axis. This configuration places a constraint on the system, as the propellant cannot be stored in a single central tank. Further constraints arose because of the extremely tight project schedule, with only 9 months from design-to-launch. Therefore, we sought existing off-the-shelf designs and hardware, where possible from UK or European sources so as to avoid any possible delays associated with obtaining the necessary export licences.

Thus, a British company, Polyflex Aerospace Limited, was selected as the valve supplier. They had already developed a cold gas thruster, in conjunction with SSTL, under a recent British National Space Centre sponsored program. This thruster is to be used on SSTL's ESAT enhanced micro-satellite program. The thruster's valve was designed for use with regulated nitrogen, giving 100 mN thrust at 4 bar chamber pressure, hence the use of butane at 2 bar for SNAP-1 was well within its capabilities

Figure 3: SNAP-1 Pipework Assembly

The most obvious feature of the complete propulsion pipework assembly (Figure 3) is that there is no propellant tank as such. The propellant is, instead, stored in 1.1 metres of coiled titanium tubing, providing 65 cm^3 (4 in^3) of storage volume. This has a number of advantages over a conventional "tank":

- There is easily-verified compliance with MIL-STD-1522A (and follow on regulations), as the system does not contain a pressure vessel, only pipework and fittings. Compliance with the standard merely requires a minimum burst of 4 x Maximum Operating Pressure, which was demonstrated in the system proof test.
- The materials costs are low - standard Airbus titanium tubing was used.
- There is an even distribution of mass along the tube.

A fill valve is welded directly to one end of the coiled tube assembly. The other end is connected to a titanium manifold. The manifold contains a pressure transducer and temperature sensors for system monitoring. Additionally, inside the manifold there are stainless steel mesh discs, which act both as filters and as heat transfer elements. The manifold has an external heater (a 15Ω commercially available resistor), which is to ensure propellant vaporisation during firings. Finally an isolation valve and a thruster valve are fitted inside the manifold. Figure 4 shows a schematic of this system.

As the system contains only a small volume of propellant, it is sensitive to leakage. Consequently all joints in the system are welded or contain double seals. The isolation valve protects against leakage from the thruster valve.

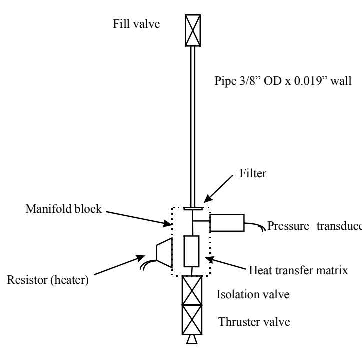


Figure 4: Propulsion System Schematic

32.6 grams of butane was loaded into the system three weeks prior to the spacecraft being shipped to the launch site (Plesetsk in northern Russia). The operation was performed in a standard laboratory fume cupboard in the Propulsion Lab at the Surrey Space Centre and (with the care required) took two engineers three hours to perform. Due to the low toxicity of butane, no additional personnel safety equipment was required - the major precaution being to avoid any potential ignition source. Once completed, no further propulsion system operations were required at launch site. For future programmes this could be a significant advantage. For example, if a future constellation of SNAPs was being launched, there would be a significant cost saving by loading propellant prior to shipping to launch site. Further details of the system can be found in [2,3].

SNAP-1 in-orbit operations

SNAP-1 was launched on a COSMOS launch vehicle on 28th June 2000, from Plesetsk, Russia, into a 650 km, sun-synchronous orbit. It was launched together with the SSTL-built Tsinghua-1 micro-satellite, and both were mounted on the primary Russian payload - a COSPAS-SARSAT (search-and-rescue) satellite called Nadezda [4].

SNAP-1 was the first spacecraft to separate, and once free, it used its Machine Vision System (based on four miniature CMOS video cameras) to obtain excellent images of the separation and deployment of Tsinghua-1 into orbit.

One of the more ambitious elements of the operations plan was to try to manoeuvre SNAP-1 back into the vicinity of Tsinghua-1 in the months following orbital injection. The ability to do this would depend critically upon the initial relative orbits of the two spacecraft, which in turn depended upon the orientation of the carrying vehicle during the separation sequence – a factor outside of our control.

Because of the low mass of SNAP-1 (6.5 kg) compared to Tsinghua-1 (~50 kg), atmospheric drag causes SNAP-1 to lose altitude rapidly relative to Tsinghua-1, thus, it was hoped that SNAP-1 would be deployed into a slightly higher initial orbit. Unfortunately the deployment was such that SNAP-1 ended up with a semi-major axis around 2 km lower than that of Tsinghua-1. This, significantly increased the ΔV required to bring the two back together to perform a rendezvous, as we first had to overcome the altitude difference, and then boost SNAP-1 to an even higher altitude to phase them correctly.

Once SNAP-1's attitude control system (a single pitch-axis momentum-wheel with magnetorquer rods) and attitude/orbit determination system (3-axis magnetometer with a 12-channel GPS receiver) had been commissioned and verified as functioning correctly, the propulsion system could be tested. This began with the first firing on the 15th August 2000.

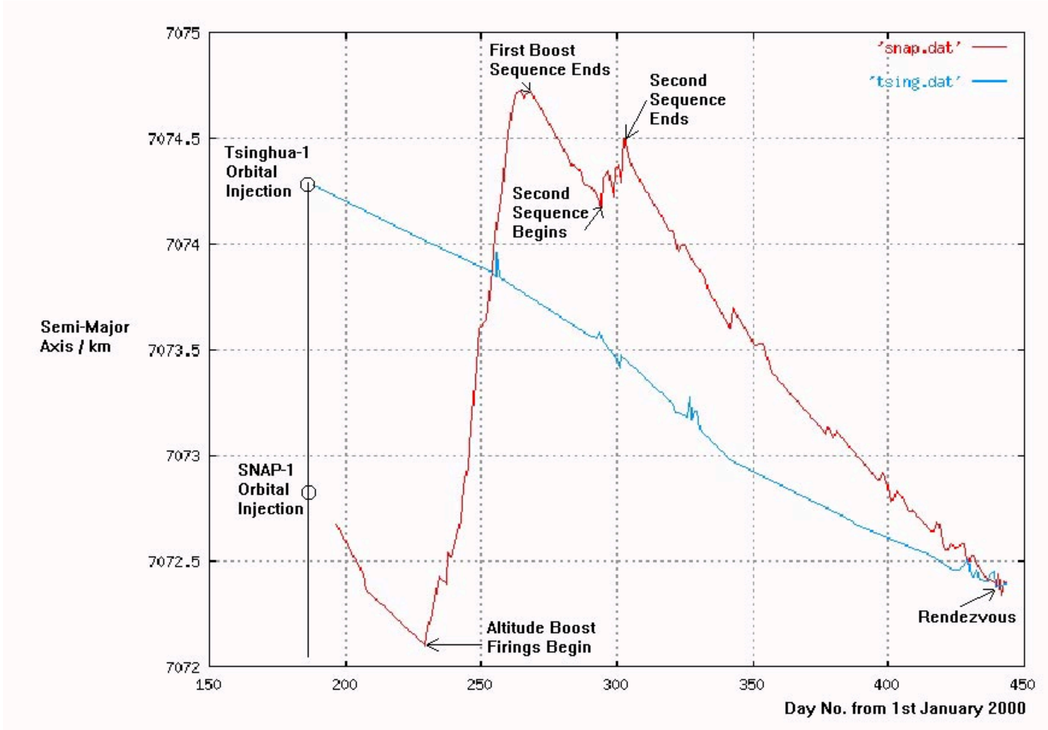


Figure 5: SNAP-1 and Tsinghua-1 Semi-Major Axis History

Initial tests showed that the propulsion system functioned correctly, and so a series of firings were begun in order to raise SNAP-1's semi major axis above that of Tsinghua-1 (Figure 5).

By September 19th, SNAP-1 had gained 2.6 km in altitude and was ~1 km higher than Tsinghua-1. A total of eighty, firings had been performed by this stage, mostly of 3 seconds duration, under the full automatic control of SNAP-1's on-board computer.

High levels of solar activity meant that the atmospheric density was higher than normal during this period, and SNAP-1 continued to fall rapidly – up to 20 m per day in absolute height terms, and ~10 m per day relative to Tsinghua-1.

Further modelling of the orbits showed that SNAP-1 needed to be boosted higher still if a close rendezvous was to be achieved. Thus, a further series of firings was undertaken from the 20th to the 29th October 2000, which boosted SNAP-1's altitude by a further 350 m before the propellant was finally depleted. In total, 98 firings were made with a total firing duration of 297.1 seconds.

After this, SNAP-1 continued to drift towards Tsinghua-1, passing its altitude on 15th March 2001, with ~2000 km along-track separation – a rendezvous of sorts!

When drag effects are taken into account, it can be seen that the first sequence of firings effectively raised the SNAP-1's orbit by between 3.1 and 3.4 km relative to where it would have been had the propulsion system not been used. Similarly, the second firing sequence raised the orbit by ~540 m relative to where it would have been otherwise.

From these figures, we calculate that the total *effective* ΔV was between 1.9 and 2.1 m/s giving a mission I_{sp} of approximately 43 s – rather lower than the theoretical value of 70 s.

Given that 32.6 g of propellant was used in 297 s of firing, the effective thrust (= $g_0 I_{sp}.dm/dt$) is calculated as 46 mN – again lower than predicted, given a firing temperature of more than 20 ^{o}C.

Firing data

Figures 6,7 and 8 show telemetry downloaded during various propulsive firings. The figures consist of:

- the pressure (data obtained from the system's pressure transducer, in bar absolute);
- the battery voltage (which indicates when the heater is switched on prior to the firing);
- the temperature (measured at the inlet to the isolation valve, next to the heater).

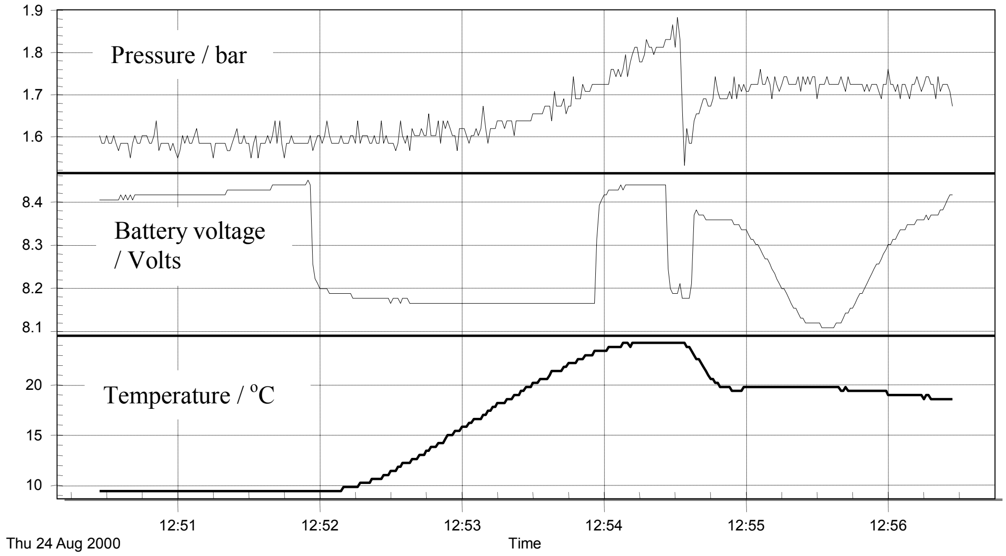


Figure 6: Data from Firing No. 4 (Typical of Early Firings)

This chart (Figure 6) shows the heater being operated for 2 minutes prior to the firing, as indicated by the dip in battery voltage.

The temperature at the manifold rises from 9 ºC to 24 ºC as a result of this. In addition, the pressure can be seen to rise from 1.58 bar to 1.88 bar, due to the temperature increase.

By performing simple calculations using Boyle's law, it is clear that the pressure rise is much greater than would be expected on the basis of heating vapour alone. This therefore indicates that there is liquid boiling near to the outlet and that this is causing the pressure to rise at such a high rate.

This phenomenon is not too surprising as the system only had 13% ullage at the start of the mission. We calculate that there is still less than 20% ullage at this firing.

The sharp drop in the pressure trace indicates the thruster firing.

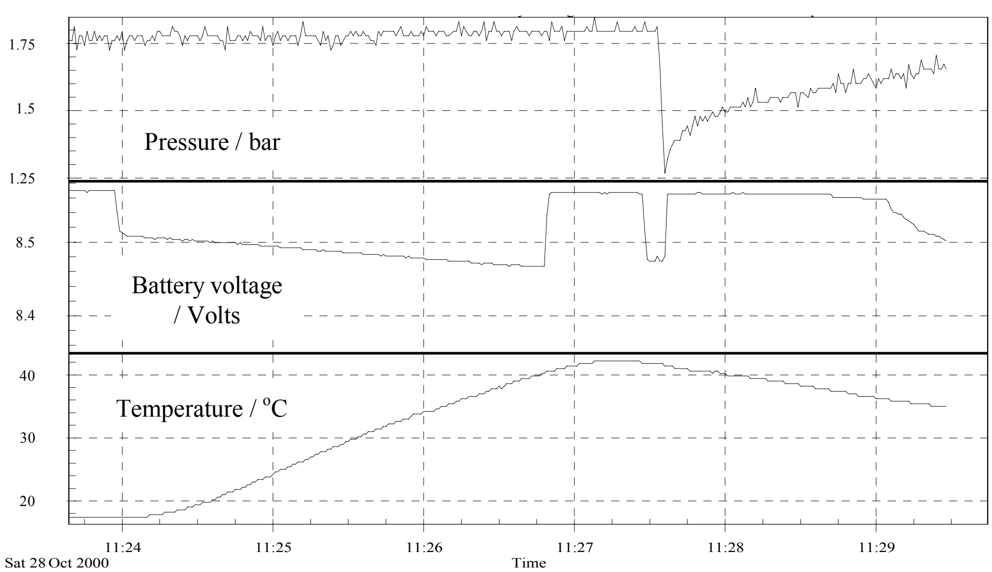


Figure 7: Data from Firing No. 93 (Just Before Propellant Depletion)

This firing (Figure 7) was the last one to be performed whilst there was still liquid left in the system at the end of the firing. After subsequent firings only vapour remained, and the pressure trace did not show the usual recovery.

The pre-firing heater sequence was of 3 minutes duration. During that time, the pressure only rose 0.05 bar from 1.75 bar to 1.8 bar. This is indicative of heating only vapour, which is unsurprising as there was only a tiny amount of liquid left at this late stage. The temperature rose 26 degrees from 17 ºC to 43 ºC.

Again, the sharp drop in the pressure trace indicates the thruster firing.

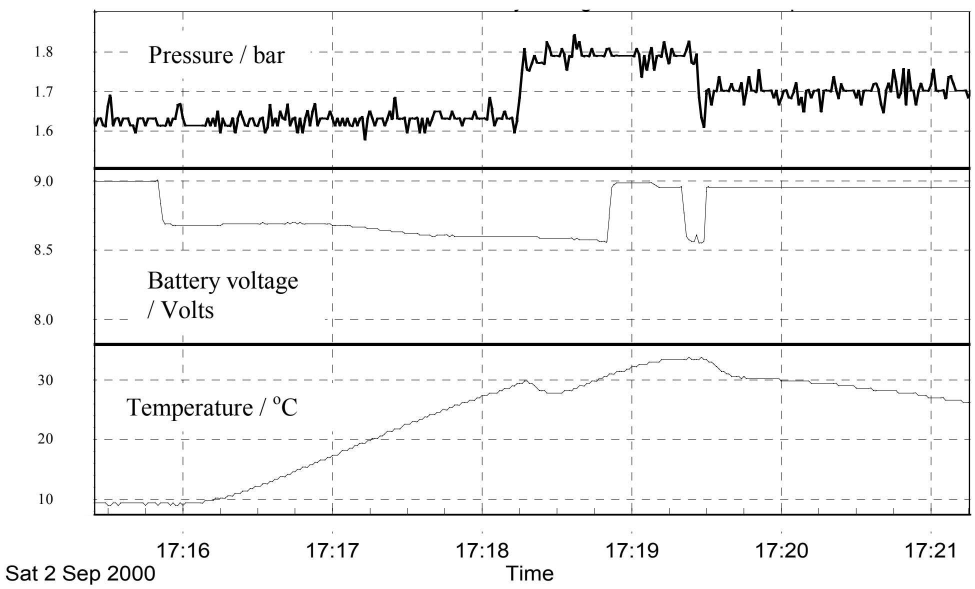


Figure 8: Data from Firing Number 20

Firing number 20 (Figure 8) occurred after a total of 60.1 seconds of operation. The heater was actuated for 3 minutes prior to the firing.

For the first 2.5 minutes of heater operation, the pressure trace rises very slowly, indicating that there is vapour at the valve inlet. However, after this there is a sudden step increase in the pressure, combined with a sudden temperature reduction - even though the heater remains on.

This seems to indicate that there was a globule of liquid butane floating near to the valve. We surmise that it must have touched the warm wall and started vaporising rapidly, giving the noted rise in pressure. The temperature dips due to the energy required to vaporise the butane, which is drawn from the manifold wall.

Analysis of performance

Figure 9 shows a plot of the height gained against the cumulative firing duration. An interesting feature to note is that during the first 20 seconds the curve is steeper than for the rest of the sequence.

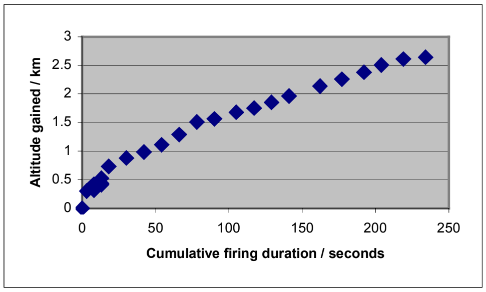


Figure 9: Semi Major Axis Gain vs. Cumulative Firing Time

This indicates that, initially, the spacecraft was gaining more altitude per second of firing duration than later. The first data show that the actual rate of height gain is greater than that expected even on the basis of the system achieving its theoretical I_{sp} performance. This can only mean that the propellant mass flow rate was greater than expected - a likely reason being that, in these early firings, some liquid phase propellant was expelled.

This ties in with the measured overall mission specific impulse being 43 seconds rather than the theoretical value of 70 seconds. The liquid expelled does not accelerate to the same exhaust velocity as the gas, so therefore less momentum is transferred to the spacecraft (per unit mass of propellant used). Indeed, this scenario is supported by the telemetry from the early firings: Figures 6 and 8, show that there was liquid phase butane around in the manifold, so it is not surprising that some was expelled. Figure 9 indicates that after 20 seconds of cumulative firing time, the rate of height increase stabilised, indicating that vapour (primarily) was being expelled by this time. In total, it would seem that some 30-40% (i.e. 10-13 grams) of the propellant was expelled in liquid form.

The conclusion to be drawn from this is that the propulsion system had inadequate ullage volume at the start of the mission. Even though the manifold heater was vaporising propellant, there was still liquid phase propellant close to the outlet. By 20 seconds into the firing sequence, the bulk of the liquid propellant seems to have been settled into the tube, with sufficient ullage for the heater to be fully effective.

Magnetic anomaly

Commissioning of the various spacecraft subsystems took place during the first 6 weeks after launch. During this period, an anomaly with the spacecraft's attitude was observed. When not otherwise controlled, the spacecraft's thruster-axis (Z-axis) appeared to track the Earth's magnetic field, which meant that there was effectively a magnet onboard. The consequence of this was that the spacecraft rotated twice in pitch each orbit. Subsequent ground tests showed that the thruster and isolation solenoid valves did indeed retain some residual magnetism, and that these were the likely cause of the observed behaviour. Although the levels of residual magnetism were tiny, they were sufficient to affect the spacecraft, as its moments of inertia are so small. This "compass" mode did not adversely affect the spacecraft's operations, however for future spacecraft, action will need to be taken to minimise the effect of any residual magnetism in the valves.

Lessons learnt from SNAP-1

The following lessons have been learnt from the SNAP-1 mission, which are being incorporated in all future SSTL missions:

A coherent propellant management strategy is required to ensure that no liquid phase propellant is expelled. This will ensure that the effective I_{sp} does not reduce below the values used in the propellant budget. Measures which can help this are to:

- ensure a large ullage at start of mission;
- add significant heater power to vaporise liquid propellant;
- have a system layout such that the thrust settles the propellant away from the tank outlet.

Also, to avoid the repeat of the magnetic anomaly, we shall:

- wire valve pairs such that their residual fields oppose each other;
- shield the valves with mu-metal if required.

Disaster Monitoring Constellation

SSTL are currently building a constellation of Earth observation spacecraft called the Disaster Monitoring Constellation (DMC), which will give daily revisits over every part of the globe. Contracts have already been placed for three of these spacecraft (ALSAT-1, UK-DMC, NigeriaSat-1). Each spacecraft will weigh 100 kg and five will be launched together on a single launch vehicle. Each spacecraft requires 10 m/s of ΔV for constellation forming, station keeping and drag compensation.

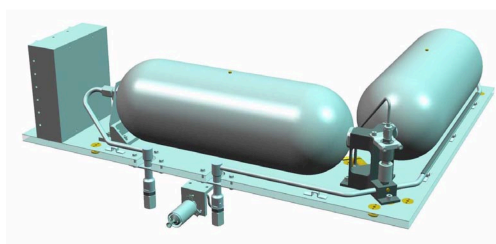


Figure 10: DMC Butane Propulsion System

Building on the success of SNAP-1, a butane system has been selected to provide the ΔV requirements for this mission. The propellant budgets show that 2.3 kg of butane is required to meet the mission with acceptable margins. Elements of the SNAP-1 propulsion system have been retained, with two major changes:

- The coiled tube arrangement used as a tank on SNAP-1 is not feasible on DMC and so two 2.5 litre conventional tanks are used (see Figure 10).
- Rather than the nozzle of the thruster being incorporated in the thruster valve, there is a separate thrust chamber assembly with an integral heater.

Completion of the first flight system, ALSAT-1, is due in October 2001.

The heated thruster assembly is designed to use 15 watts of heater power. This will ensure that any liquid phase butane will be vaporised. However, to make sure, there are additional features in the system which should prevent liquid propellant from reaching the thruster. In addition, the heated thruster will act as a resistojet and the specific impulse performance will be increased over that of butane in cold gas mode.

Further details of the DMC propulsion system are given in [5].

DMC Development test model

A development model has been designed and built to simulate the DMC butane propulsion system (see Figure 11). Two Perspex tanks hold butane in sponges, such that the propellant can be observed.

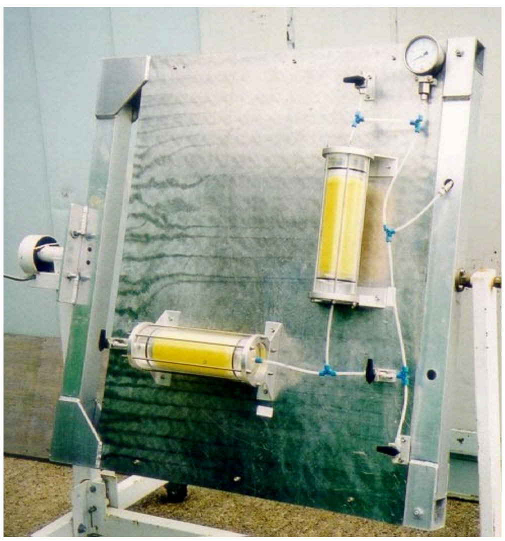


Figure 11: DMC Development Model

The development model is being used to:

- perform butane flow testing;
- perform thruster firing in an evacuated chamber;
- develop propellant loading techniques;
- determine tank-to-tank transfer of propellant under thermal gradients.

Conclusions

A low cost butane propulsion system has been successfully flown on Surrey's SNAP-1 spacecraft – the first nano-satellite to successfully demonstrate an orbit-control propulsion system. Due to its simplicity, we were able to design, build and test the propulsion system in 7 months, as necessary given SNAP-1's rapid development schedule. Once in orbit, the propulsion system was used to raise the orbit of SNAP-1 by 2.6 km and then ~0.4 km in absolute terms, giving ~3 km in total. However, once the effects of atmospheric drag have been taken into account, this translates to an equivalent of almost 4 km change in height.

The overall mission specific impulse achieved (43 s) was significantly lower than the theoretical figure (70 s). This has been shown to be due to liquid-phase propellant being expelled at the start, which resulted in a much reduced efficiency. Even so, a total mission ΔV of ~2 m/s was achieved with just 32.6g of butane propellant.

This, and other minor anomalies, such as the unexpected residual magnetism in the thruster valves, has been been fed back into the design of SSTL's next generation of spacecraft: the Disaster Monitoring Constellation.

Three butane propulsion systems are being built for the DMC spacecraft. They rely heavily on the SNAP-1 heritage.

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